

Life–Cycle Robustness: Quantification And Challenges

Roman Wendner

Research Associate, Institute of Structural Engineering, University of Natural Resources and Applied Life Sciences, Vienna, Austria

Alexios E. Tamparopoulos

Research Associate, Institute of Structural Engineering, University of Natural Resources and Applied Life Sciences, Vienna, Austria

Konrad Bergmeister

Professor, Institute of Structural Engineering, University of Natural Resources and Applied Life Sciences, Vienna, Austria

ABSTRACT: Life-cycle robustness is achieved when a structural member or a system is designed to maintain its intended function and required safety level within its desired life-cycle. The different character of effects that each element of the system needs to undergo (damage, ageing, extreme events, changes in usage) in conjunction with the diversity in the intrinsic material properties, form a demanding problem. Further complexity emerges when one realizes that time is not simply a variable, but a factor permeating model choices and uncertainty representation approaches. Different effects in the load side, and properties in the resistance side develop differently in time. Depending on the scale of the problem, the spatial randomness of materials such as concrete may be relevant for the accurate quantification of failure probabilities, and may require careful modelling, even at a mesoscale. For a long-term analysis, where the influence of uncertainties may dominate over predictability, robust design concepts and analyses methods that are relatively insensitive to small variations in variable inputs related to secondary effects and processes can prove decisive. On the computational side, challenges are associated with the computational cost of simulations and nonlinear analyses required to determine time-variable reliability profiles, considering all likely scenarios. Furthermore, statistical characteristics of the inputs, in particular their tail behaviour and their statistical dependence, needs to be properly captured and reproduced while maintaining sufficiently small sample size, and thus acceptable computational cost. Within this contribution, a framework for the quantification of life-cycle robustness is presented in the context of fasteners subjected to sustained load and extreme events. The emerging challenges are presented and briefly discussed.

1. INTRODUCTION

Life-cycle robustness aims to expand the concepts of safety, sustainability and cost-efficiency of infrastructure to include highly uncertain and unforeseen events. In particular, it can be defined as the ability of a component or a whole system to maintain its intended function and required safety level in spite of damage, ageing, extreme events, or changes in usage throughout its life-cycle. Robustness can have several different aspects, since it needs to include installation, operation, demoli-

tion, and recycling phases. Each of these perspectives faces different challenges, as it is subjected to different actions and variations. A careful analysis and synthesis of those aspects reveals more challenges and uncertainties, as the level of detail increases. It also discloses the weaknesses of some currently adopted assumptions in the context of life-cycle evaluation and robust design approaches. In the present paper, the requirements of an integrated life-cycle robustness design and application framework, focusing on fastening systems are dis-

cussed, the major challenges of this concept are briefly reviewed, and the main expected prospects that arise from the application to fastening systems are outlined (Wendner and Tamparopoulos, 2014). Finally, computational aspects of life-cycle robustness on fastening systems are presented.

The requirements of life-cycle robustness on fastenings cover a broad range of topics that should be addressed by an integrated approach. Design requirements aim at formulating consistent design codes through experimentation and verification. Development may refer to new optimised products, and accelerated production processes for existing ones. Progress on this front is constantly required, owing to new developments in construction materials with largely unknown long-term behaviour. Testing methods are required to investigate the effect of geometrical and material properties, including ageing, on the load bearing capacity. It is important to verify numerical computations for the different failure modes, types of systems, base materials, and loading conditions. The type and volume of acquired data often stress the need for data analysis methods that go beyond traditional statistical inference. In the installation procedure, particularly in critical infrastructure, geometrical tolerances, variations, and possible human errors need to be taken into account. Adequate performance levels need to be prescribed, varying from serviceability to ultimate capacity. Sufficient safety margins are required in order to ensure robustness throughout the whole service life, and issues related to possible secondary consequences, progressive damage and disproportional failure effects should be investigated. Sustainability in the disassembling and disposal process should include provisions that extend beyond the anchor's life time. Finally, many aspects are of great importance with respect to cost (experimentation, intervention, optimised maintenance planning, rehabilitation, renovation, repair, replacement), when viewed over the intended lifespan.

In each of the life-cycle robustness perspectives, different challenges may arise. As the level of detail in the investigation increases, more challenges and uncertainties can be disclosed. Temporal effects in-

clude processes, actions, influences, and secondary effects that develop differently in time. System diversity emerges from variations in the component formulation, failure modes, geometry, cracking of concrete, reinforcement type, loading type, different base materials or intended applications. Performance is assessed in the regimes of small probabilities, where the influence of uncertainties can be large; furthermore, nonlinear complexity, sample size, model uncertainty, and possible dependence structure can seriously affect computations. Uncertainties of various types are confined in the mechanical properties of materials, geometrical tolerances and installation variations, extreme events, environmental influences, and degradation processes. Structural and statistical dependence may lead to unrealistic estimations, in particular in the area of low target failure probabilities, when several input variables are considered. Multi-scale modelling approaches aim to connect the two different perspectives, namely the macroscopic behaviour of fastening systems, and the micro-scale properties of base materials, e.g. concrete. The costs resulting from the sheer volume of required tests and from the equipment for performing non-destructive testing for developing accurate models comprise a major challenge. A multidisciplinary approach is needed in order to develop an efficient life-cycle robustness framework.

There are several prospects of developing an integrated multidisciplinary approach of life-cycle robustness of fastenings. Firstly, incorporating state-of-the-art in research on concrete behaviour (creep, shrinkage, etc.) and on other base materials will allow for developing much more refined prediction models (Wendner et al., 2014). In this context, existing research on physics and material science can be utilised. The quest for performance-based design concepts, transparent safety levels, and durability can lead to processes that realistically simulate the behaviour of fastening systems. Stochastic models for input variables in space and time are constantly being developed (Eliáš and Vořechovský, 2012). Uncertainty importance analyses focusing on the intended applications can indicate the parameters that mostly influence the perfor-

mance of fastenings in time. Thus, research efforts can be efficiently allocated to base material properties, time effects, loading scenarios, fracture development, testing procedures, and representation of spatial or other variations. More practical and no less important prospects include the study of installation, maintenance, repair, and replacement within a unified framework. Construction planning can take great advantage of realistic evaluations of system performance or cost efficiency. Fast and automated construction techniques can be developed, and future market demands can be captured. The assessment of existing fastening systems can significantly reduce cost and increase the reliability of complex systems. Currently used reliability indices reflect only the failure frequency and not the consequences of failure. On this front, utility-based performance and safety evaluation can facilitate fastening applications. In the next years, a more effective use of new laboratory technology is expected. Accurate testing procedures can be formulated, following the technological developments in data acquisitions equipment and the related analysis methods.

2. LIFE-CYCLE ROBUSTNESS QUANTIFICATION FRAMEWORK FOR FASTENING SYSTEMS

2.1. Preliminaries

Anchorage are very important for integrating precast elements, and for strengthening and retrofitting. They allow the connection of new load bearing structural members with existing elements, as well as the installation of new, not structurally relevant, elements, e.g. sunshades. Therefore, fastenings are important for any adaptation of existing infrastructure, and for the life-cycle design of new structures. The economic significance of fastenings is indicated by the fact that the potential damage caused by failed fastening elements can be by several orders of magnitude higher than the value of the products themselves. It is also highlighted by the use of fastenings as key-elements of critical infrastructure, such as power plants, hospitals, and utility line systems.

The current state of fastening technology reflects only 25 years of systematic research. So far, practice has been limited to simple solutions, to naïve

methods for estimating lifetimes, to the assumption of unreinforced concrete, and to mere addition—as opposed to realistic combination—of safety factors. The load carrying capacity has been mostly studied under static short-term but not under dynamic loads. Deeper understanding regarding the load carrying mechanisms faces a number of challenges. More accurate prognostic models can offer an optimised design of new fastening systems, and a reliable assessment of existing systems. Therefore, such models will facilitate efficient maintenance management over the full product lifetime.

A fastening system is an arrangement of anchors and other structural members formed into a broader structure. The performance of the system is determined by the performance of its individual components, and by the arrangement layout. In the following, we will confine ourselves to a single anchor system. In order to realistically assess and predict the performance of anchors, and formulate models for their life-cycle robustness, it quickly becomes evident that time is not simply a variable, but rather a factor permeating fundamental model choices and uncertainty representation approaches. In fact, the life-cycle performance and robustness of fastening systems is influenced by several time-dependent processes, which alter the initially assumed mechanical characteristics. Some of those effects develop monotonically in time—albeit not necessarily in a linear fashion—whereas others have a periodical nature. Environmental influences may occur due to concrete carbonation, chloride effects, steel corrosion, UV radiation, and freeze-thaw cycles. Concrete creep may have significant influence on the long term performance; therefore, models that accurately describe this phenomenon are needed (Bažant, 2001). Random actions (imposed by fatigue, fire, earthquakes, explosions, traffic accidents, etc.) cannot always be foreseen and modelled akin to the typically encountered loading scenarios. Monitoring and updating of prediction models can be challenging, since concrete fracture initiates at a very low scale. Finally, possible consequences of ageing need to be investigated, not simply in the narrowed view of the fastenings themselves, but rather with respect to the broader system

which they operate in.

Life-cycle robustness design faces a multitude of aleatory and epistemic uncertainties. The amount of deviation to be expected depends both on the randomness in the applied loads as well as on the amount of uncertainty in the mechanical properties of the used materials, due to inherent variabilities and heterogeneities. In fact, a significant part of uncertainty can be attributed to the heterogeneity of concrete at lower scale, which is linked to a variety of macroscopic effects during failure. However, the mechanical properties of materials and members after many years of operation are largely unknown. Further uncertainties arise from geometrical tolerances and variations in the installation procedure. Tolerance against installation inaccuracies (installation robustness) constitutes a major challenge. Furthermore, resistance against extreme events or environmental influences faces the problems of unpredictability and intangibles in the account of consequences. If the temporal dimension is added to the analysis (as required for any life-time prediction) the uncertainty associated with the predicted mean response increases significantly with the time span of extrapolation—in particular if degradation processes and extreme events are to be considered.

2.2. Quantification of performance

The aim of a quantification framework for life-cycle robustness is to describe a model for the performance of fastening systems with changing properties, subjected to uncertain load scenarios (sustained load and accidental events). The requirement that resistance is not smaller than action ($R \geq S$) is not straightforward to solve in order to analytically obtain failure probabilities. Firstly, both resistance $R(t)$ and action $S(t)$ are time-dependent. In addition, at any given time t , the system state depends on the load history. This strongly affects, not only the resistance, but also the limit state that needs to be solved to obtain failure probabilities. Hence, R and S are generally not independent. Finally, the system state (reflected mainly as a result of ageing and degradation) is governed by stochastic processes in concrete, steel or other materials, largely unknown to date. Other problems associated with the system setup include nonlinearity of the system

behaviour, effective load event combination, efficient sampling and simulation. A predictive model can be supported by observations on fracture or displacement to describe the transition of changes in load S to changes in resistance R .

The resistance of the system can be written as $R = R(t)$. To emphasise that R is not merely a deterministic function of time, but rather a random variable dependent on the variable mechanical properties and the load history, one can write:

$$R = R(t|L(t)) = R(t|\tilde{x}(t), S_{\tau=0}^t) \quad (1)$$

where $L(t)$ is the system state at time t , the vector $\tilde{x}(t)$ represents the mechanical properties at time t , and $S_{\tau=0}^t$ expresses the complete load history. The vector of random mechanical properties \tilde{x} exhibits three dimensions: the statistical variability (described e.g. by proper distributions and possibly a correlation matrix), the spatial variability (described e.g. by a random field), and a time dependence, since the properties change over time, while degradation occurs due to environmental influence. When field data, such as displacement measurements, are collected through monitoring, all those types of uncertainties are involved in the observations. Therefore, a mere collection of data is not sufficient, without studying the individual effects and processes.

In terms of remaining lifetime, reliability can be defined as the probability that the system will perform its intended function under specified design limits (Pham, 2006). If T is the random variable denoting the time-to-failure, with probability function $F(t)$, then the reliability of the system is:

$$\bar{F}(t) = P(T > t), t \geq 0 \quad (2)$$

Damage models can introduce information on the lifetime T by describing the state of damage of the system at a given time t as a random variable D_t (Aven and Jensen, 2013). Then:

$$T = \inf \{t > 0 : D_t \geq D_u\} \quad (3)$$

Therefore, the lifetime is defined as the first time the (total) damage reaches a given level D_u . Here, D_u can be a constant or, more general, a random

variable independent of the damage process. In that case, the observed damage process does not carry the entire information about the failure state. Damage can be viewed as a cumulative hazard affecting the system, and described as a non-decreasing stochastic process (Singpurwalla, 2010). This compound process can be viewed as a composition of three processes:

1. A process $X_t^{(1)}$, representing the occurrence of extreme loads;
2. A process $X_t^{(2)}$, representing the damage evolution between $X_t^{(1)}$ events;
3. A process $X_t^{(3)}$, representing the possible damage owing to the occurrence of a $X_t^{(1)}$ event at time t .

For $X_t^{(1)}$ a counting process with constant appearance rate λ (e.g. a Poisson process) can be used to express the occurrence of events in time:

$$P[N(t+s) - N(t) = n] = e^{-\lambda s} \frac{(\lambda s)^n}{n!} \quad (4)$$

where N is the number of occurrences. In the case of the system of concern, one can assume more than one independent processes, in place of $X_t^{(1)}$, to account for the different event types (wind, extreme traffic load, snow, earthquake, etc.) In any case, the occurrence times are given by an increasing sequence $0 < t_1 < t_2 < \dots$ of random variables. Each point t_j corresponds to a random mark D_j that describes the additional damage induced by the j th load event.

For $X_t^{(2)}$, the damage evolution between events can be modelled as a gamma process, where the nonnegative increments are assumed to be distributed as gamma distributions (Phadia, 2013). Let $G(\alpha, \beta)$ denote the gamma distribution with shape parameter $\alpha > 0$ and scale parameter $\beta > 0$, $\alpha(t), t \geq 0$ be an increasing left continuous function such that $\alpha(0) = 0$. Moreover, let $X_t, t \geq 0$ be a stochastic process such that (i) $X_0 = 0$, (ii) X_t has independent increments in non-overlapping intervals, and (iii) for $t > s$, the increment $X_t - X_s$ is distributed as $G(c(\alpha(t) - \alpha(s)), c)$, where $c > 0$ is

constant. Then X_t is said to be a gamma process with parameters, $c\alpha(t)$ (the mean of the process) and c (the precision or scale parameter). Gamma processes have an infinite number of increments in a finite interval of time, and are therefore suitable for describing wear caused by continuous use (Singpurwalla, 2006).

For $X_t^{(3)}$, the damage amounts D_j induced by the random events in the simplest case can be modelled as i.i.d. random variables. However, D_j depends also on the current state of the system, and possibly on the entire load history, thus:

$$D_j(t) = D_j(t|\tilde{x}(t), S_{\tau=0}^t) \quad (5)$$

The simulation of the aforementioned compound process can be described as follows: At the time $t = 0$ the system has a residual damage capacity D_u when it begins to operate under sustained load and undergoes wear e.g. due to ageing, described by a stochastic process of the $X_t^{(2)}$ type. The parameters of the process depend on the initial state of the system. At time $t = t_1$, given by a process of the $X_t^{(1)}$ type, an excessive load event occurs; at this point, the system state has suffered a damage D_{01} due to ageing, and it has a residual damage capacity $D_u - D_{01}$. The extreme event induces a random damage D_1 that depends on the load history and the system state. The system undergoes a deterioration D_{12} until the next point t_2 where an event occurs, inducing an additional damage, and so on. If the residual damage capacity is greater than the ultimate level D_u , then the process continues, until failure.

A Monte Carlo simulation of this system can yield the distribution of lifetimes. The availability of the lifetime distribution that includes all types of loading scenarios can allow for estimating safe values, in the sense of statistical quantiles, with a desired confidence level.

3. CONCLUSIONS

In recent years, steadily increasing budgetary constraints have led to a strengthened awareness regarding the importance of life-cycle performance and cost considerations. The tight dependency of

society with the proper functioning of infrastructure, is linked to higher exposure and economic significance of structural systems. Life time design of infrastructure and extension of existing structures has become increasingly important (Bergmeister, 2012). Numerically and experimentally based reliability assessment methods with respect to different actions have been developed (Strauss et al., 2013). However, up to now maintenance aspects hardly enter the decision process regarding the construction of new buildings or structures. Moreover, most of the research progress in material science, in sophisticated testing procedures, or in uncertainty analysis remain confined to simple theoretical conceptions. In the present paper, the requirements of a desired framework for life-cycle robustness of fastening systems were outlined. Addressing the emerging challenges in this venture can pave the way to new prospects and theoretical advancements as well as to novel construction approaches.

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